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STRAINS

ON

BRACED IRON ARCHES

AND

ARCHED IRON BRIDGES.

Illustrated Graphically.

BY

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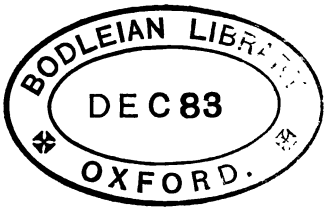
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PREFACE.

EVER since I entered the profession of Engineering, which is now twenty-four years ago, I have always had one fixed idea, that if the parallelogram of forces were applicable in solving the strains on any one structure, it should be equally applicable in the solution of others, the only difficulty being how it should be applied; and the late Professor Clark Maxwell has by his system of the closed polygon greatly contributed to this result.

As I have never seen or heard of any work wherein the solution of the arch was arrived at purely by the parallelogram of forces, I am tempted to submit the result of my researches in this direction to the profession, and at the same time to acknowledge my indebtedness to the following authors: to Professor Fleeming Jenkin for his pamphlet, which first gave me the idea that the primary object to be sought for in the arch was the "horizontal thrust," and to Mr. Stoney, for his theory as to the transmission of the thrusts through the crown of the arch.

A. S. H.

ARCHES AND ARCHED BRIDGES.

On the 13th of December, 1869, Professor Fleeming Jenkin read a paper before the Royal Scottish Society of Arts, Edinburgh, on "Braced Arches and Suspension Bridges," which paper he afterwards reproduced in the form of a pamphlet. He therein says:—"Few engineers are aware of the difficulty of calculating the strains on a stiff-arched rib held between abutments."

However, he then proceeds by a method, to which he acknowledges his indebtedness to the late Professor Clark Maxwell's paper, which was published in the "Philosophical Magazine" of April, 1864, and arrives by laborious calculations at the values of the *horizontal thrusts* for each load, which he calls H, and by adding these together, then laying down the total horizontal thrust, and applying Professor C. Maxwell's system of closed polygons,* arrives at the strains on the different parts of the arched bridge.

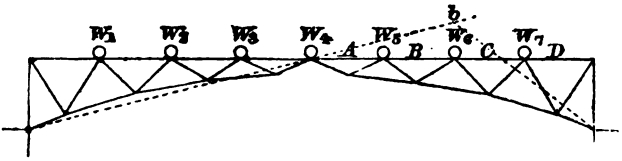
Now the object of the present treatise is to arrive at these strains graphically, and the horizontal thrust will be represented by the letter T throughout instead of H.

In Mr. Stoney's book, "Theory of Strains," he gives an example of a similar arch, Fig. 1; and he argues that the direction of the thrust for a load, on either side of the centre of the arch to the furthest abutment from the load,

* For the information of those readers of this work who are unacquainted with the late Professor Clark Maxwell's method of working out strains by his system of the closed polygon, the Author begs to refer them to the Professor's own works, or to an excellent treatise of the Chatham course, entitled "Instruction in Construction," by Col. Henry May, C.M.G., R.E., in which the method is fully explained.

must pass through the crown of the arch. Or that it must be assumed that the lower flange is not continuous across the crown of the arch, but that the structure is hinged at the crown or point W_4, Fig. 1

Fig. 1.



He then proceeds, by working down these diagonal thrusts, and with the reactions at the piers, to obtain the strains on the arched bridge.

It then occurred to the Author that if Mr. Stoney's theory were correct, he should be able, by setting up the proper reactions at the abutments, on these same *diagonal* thrusts, obtain the thrusts T for each abutment, and which thrusts *must of necessity be equal*, or else the arch would move sideways. Then, having obtained these, and applying Maxwell's method of closed polygons, he would arrive at the strains on the different portions of the arch, which he did with the most happy result, as his strains agreed with Mr. Stoney's.

Mr. Stoney is, however, perfectly warranted in his theory as to the manner of the transmission of the strain; for the law holds good just the same for girders with parallel booms and for bowstring bridges, or any girder where there is a horizontal tie performing the function of the abutments in an arch.

Take, for example, a plate girder, say 100 feet span, 10 feet deep, loaded with one ton per foot run; the load assumed to be on top and distributed as shown, Fig. 1, Plate I., there would be 10 tons at each point, = W. Then applying Mr. Stoney's theory that the strain must pass through the crown at centre, draw the diagonal AR_2; draw a perpendicular from the load W_4, cutting this line in B, and join BR_1, next setting up the vertical reactions which are

in this case $\frac{3}{10}$ $W_4 = R_1 x$ on R_1, and $\frac{7}{10}$ $W_4 = R_2 z$ on R_2; then drawing the horizontal lines, T_1 and T_2, they will be found each equal to 12·5 tons; next taking out the horizontal thrusts for each load in a similar manner, we can write them down thus:—

	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}
T_1 or T_2 =	2·5	7·5	12·5	17·5	22·5	22·5	17·5	12·5	7·5	2·5

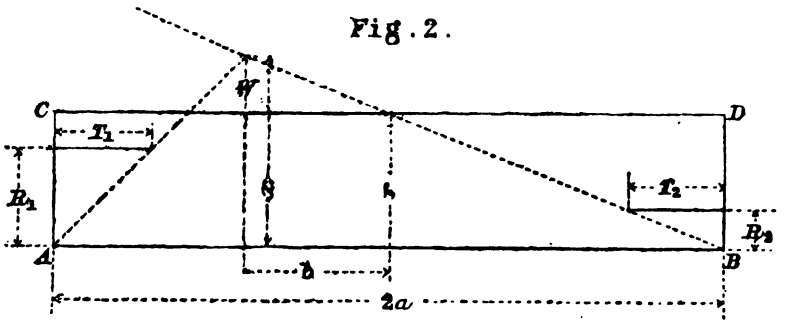
which added up together gives T = 125 tons, and is the total horizontal thrust or strain at the centre of the girder. Check this by the old formula $\frac{W L}{8 D}$ for an equally distributed load; substituting values there results

$$\frac{100 \text{ tons} \times 100 \text{ feet}}{8 \times 10 \text{ feet}} = 125 \text{ tons.}$$

To check by calculation the above values for T_1 or T_2, with the load at any point, is easily done by the formula $\frac{W\ (a - b)}{2\ r}$, where W = the weight, $a = \frac{1}{2}$ span, b = the distance of the load from the centre of span, and r = the rise or depth at the centre.

To prove the above, and show that $T_1 = T_2$,

Fig. 2.



Let A B C D, Fig. 2, be a girder or beam,

$2a$ = the span A B,

r = the rise or depth at centre,

b = the distance of the load from centre,

W = the load or unit of weight.

Then by similar triangles

$$T_1 : R_1 : : a - b : x \text{ and } x : a + b : : r : a,$$

$$\therefore T_1 = \frac{R_1\, a\, (a - b)}{r\, (a + b)} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

also $$T_2 : R_2 : : a : r,$$

$$\therefore T_2 = \frac{R_2\, a}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

but $R_1 = \frac{W\,(a + b)}{2\,a}$; substituting this for the value of R_1 in equation 1, there results

$$T_1 = \frac{W\,(a + b)\,(a - b)\,a}{2\,a\,r\,(a + b)} \quad \text{or } T_1 = \frac{W\,(a - b)}{2\,r};$$

again $R_2 = \frac{W\,(a - b)}{2\,a}$ substituting this for the value of R_2 in equation 2, there results

$$T_2 = \frac{W\,(a - b)\,a}{2\,a\,r} \qquad \text{or } T_2 = \frac{W\,(a - b)}{2\,r}.$$

Hence $$T_1 = T_2 = \frac{W\,(a - b)}{2\,r}.$$

Which stated in words is, that any weight multiplied by the distance from the nearest abutment, and divided by twice the depth or rise in centre, will give the strain or horizontal thrust through centre.

Next suppose a bowstring girder be taken (Fig. 2, Plate I.), 80 feet span, 10 feet deep in centre, loaded with one ton per foot run, and assume that the load of 80 tons is distributed so that there shall be 5 tons on each apex at the intersection of bars on the bow or compression-beam.

Then take out the strain for the single load, W_6, by Maxwell's diagrams, Fig. 3, Plate I., and then calculate the horizontal thrust (T) at centre by the formula given above, $T = 7 \cdot 5$ tons; lay down this thrust on the diagram, and it will be found that the figure of polygons turns on the point X, and that by dropping a perpendicular from this

point on to the two compression-bars, A and A′ in the diagram of strains (and the space between which gives the strain on the vertical (1) at centre), the diagram could have been worked backwards from the points so obtained to the abutments. Similarly, if first the strains are obtained by Maxwell's diagrams for the girder fully loaded as shown, Fig. 4, Plate I., and then calculate the horizontal thrust for the girder fully loaded, T, the total horizontal thrust will be obtained equal to 80 tons. Laying this down (xy) on the diagram, it will be found that the polygons turn on this point x, although the strain on the centre of tension-beam of the girder is a trifle less.

Having shown by the foregoing that the horizontal thrust holds good for the bowstring bridge, it is only natural to suppose that it should hold good for the arch, as the bowstring is simply an arch having the horizontal thrust met by the tie, which in the arch has to be done by the abutments. Again, in the bowstring the bow is kept in position by the bracing, whereas in the arch this stiffness has to be obtained by the extrados and intrados of the arch-ring, and the bracing between them.

In the next chapter it will be shown how, having obtained the horizontal thrust, the strains on every part of a braced iron arch are to be arrived at.

CHAPTER I.

THE ARCH.

Example I.

Take a semicircular arch, 80 feet span out to out, because the arch differs from the girder in this respect, that in the girder the span is taken as between the points of support, whereas in the arch the points where both the reaction of the load and the horizontal thrust of the abutments act must be taken. Let it be 8 feet deep (this is excessive, but was done for the sake of the diagrams of strains), with parallel extrados and intrados, and braced as shown on Fig. 1, Plate II., with the diagonals in black lines, loaded at each apex with one ton, and firmly held at the points of support, R_1 R_2.

Then proceed to measure or calculate the distances of the various loads from the centre, so as to obtain the reactions and horizontal thrusts, which may be obtained either graphically or by calculation (the latter preferred), as given at page 7.

They may then be written down thus:—

	Distance from centre.	T_1 or T_2	R_1	R_2
W_1	39·23	0·009625	0·990375	0·009625
W_2	36·95	0·038125	0·961875	0·038125
W_3	33·26	0·08425	0·91575	0·08425
W_4	28·23	0·147125	0·852875	0·147125
W_5	22·22	0·22225	0·77775	0·22225
W_6	15·30	0·30875	0·69125	0·30875
W_7	7·80	0·4025	0·5975	0·4025
W_8	Nil	0·5	0·5	0·5
W_9	7·80	0·4025	0·4025	0·5975
W_{10}	15·30	0·30875	0·30875	0·69125
W_{11}	22·22	0·22225	0·22225	0·77775
W_{12}	28·23	0·147125	0·147125	0·852875
W_{13}	33·26	0·08425	0·08425	0·91575
W_{14}	36·95	0·038125	0·038125	0·961875
W_{15}	39·23	0·009625	0·009625	0·990375
Total horizontal thrust T =		2·92525		

Having obtained the total horizontal thrust for the arch loaded with one ton on each apex, next proceed to take out the strains for the arch, Fig. 1, Plate II., as shown with the diagonals in black lines, leaving out those in dotted lines.

To any scale of parts lay down this thrust T, as shown in Fig. 2, Plate II., and at right angles from this line lay off the loads, putting half of W_8 each side of the line, it being a central load (only half the figure is shown in the diagram, as the other half for the other side of the arch would be simply a repetition, only upside down), and set out the remainder of the loads.

Then, by applying Maxwell's diagrams, and working from the horizontal thrust and the weights already laid down, the strains on every bar are arrived at when the arch is fully loaded with one ton on each apex. The letters and figures on this diagram of strains correspond with those on the sketch of the arch, Fig. 1. These strains are given in the last column of Table I., but the body of the Table has been compiled by taking each load out separately, and the method of working them out is shown by Diagrams 1 to 8, Plate III., to which reference will be made hereafter.

TABLE I.—Table of Strains on the Arch, Fig. 1, Plate II., with the Diagonals in Black Line.

Compression +. *Tension* −.

Extrados.

	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}	W_{11}	W_{12}	W_{13}	W_{14}	W_{15}	Greatest Compression. +	Greatest Tension. −	Fully Loaded.
H	+1·063	+1·013	+0·923	+0·808	+0·668	+0·508	+0·332	+0·152	+0·120	+0·092	+0·066	+0·042	+0·025	+0·011	+0·003	..	..	+5·826
G	+0·069	+1·204	+1·070	+0·894	+0·680	+0·434	+0·168	−0·114	−0·092	−0·070	−0·050	−0·036	−0·020	−0·009	−0·002	+4·519	−0·393	+4·126
F	+0·058	+0·235	+1·352	+1·108	+0·814	+0·476	+0·108	−0·272	−0·224	−0·170	−0·126	−0·084	−0·049	−0·022	−0·006	+4·151	−0·953	+3·198
E	+0·048	+0·193	+0·424	+1·446	+1·068	+0·634	+0·160	−0·330	−0·270	−0·206	−0·152	−0·100	−0·058	−0·027	−0·007	+3·973	−1·150	+2·823
D	+0·038	+0·151	+0·331	+0·576	+1·428	+0·900	+0·324	−0·274	−0·228	−0·174	−0·126	−0·084	−0·048	−0·022	−0·006	+3·748	−0·962	+2·786
C	+0·027	+0·109	+0·242	+0·420	+0·634	+1·264	+0·588	−0·114	−0·096	−0·076	−0·052	−0·034	−0·020	−0·010	−0·002	+3·284	−0·404	+2·880
B	+0·018	+0·072	+0·157	+0·276	+0·414	+0·576	+0·946	+0·148	+0·118	+0·088	+0·066	+0·042	+0·026	+0·011	+0·003	..	..	+2·961
A	+0·009	+0·038	+0·085	+0·146	+0·224	+0·306	+0·406	+0·502	+0·406	+0·306	+0·224	+0·146	+0·085	+0·038	+0·009	..	..	+2·930
Intrados.																		
K	−0·086	−0·057	−0·005	+0·062	+0·142	+0·234	+0·334	+0·444	+0·356	+0·274	+0·196	+0·130	+0·074	+0·034	+0·008	+2·288	−0·148	+2·140
L	−0·074	−0·297	−0·189	−0·046	+0·128	+0·324	+0·554	+0·770	+0·618	+0·480	+0·342	+0·228	+0·131	+0·059	+0·015	+3·649	−0·606	+3·043
M	−0·061	−0·246	−0·540	−0·314	−0·040	+0·272	+0·616	+0·970	+0·784	+0·604	+0·434	+0·288	+0·166	+0·074	+0·019	+4·227	−1·201	+3·026
N	−0·048	−0·193	−0·424	−0·736	−0·356	+0·076	+0·550	+1·040	+0·838	+0·644	+0·466	+0·310	+0·177	+0·080	+0·021	+4·202	−1·757	+2·445
O	−0·035	−0·139	−0·308	−0·532	−0·810	−0·258	+0·346	+0·970	+0·786	+0·604	+0·434	+0·290	+0·166	+0·075	+0·019	+3·690	−2·082	+1·608
P	−0·022	−0·089	−0·196	−0·338	−0·512	−0·714	+0·014	+0·770	+0·624	+0·476	+0·344	+0·228	+0·131	+0·059	+0·015	+2·661	−1·871	+0·790
Q	−0·010	−0·042	−0·091	−0·158	−0·238	−0·334	−0·434	+0·440	+0·354	+0·274	+0·198	+0·132	+0·074	+0·033	+0·008	+1·513	−1·307	+0·206
Bars.																		
16	−0·116	−0·076	−0·006	+0·084	+0·192	+0·314	+0·452	+0·596	+0·482	+0·368	+0·266	+0·176	+0·101	+0·045	+0·011	+3·087	−0·198	+2·889
15	+0·071	+0·046	+0·004	−0·050	−0·118	−0·194	−0·276	−0·364	−0·292	−0·222	−0·162	−0·106	−0·061	−0·028	−0·007	+0·121	−1·880	−1·759
14	+0·016	−0·324	−0·248	−0·144	−0·018	+0·124	+0·280	+0·446	+0·358	+0·274	+0·198	+0·132	+0·076	+0·034	+0·009	+1·947	−0·734	+1·213
13	−0·026	+0·187	+0·150	+0·100	+0·038	−0·030	−0·108	−0·184	−0·148	−0·114	−0·082	−0·054	−0·032	−0·014	−0·004	+0·475	−0·796	−0·321
12	+0·017	+0·068	−0·476	−0·362	−0·224	−0·070	+0·100	+0·274	+0·224	+0·170	+0·124	+0·082	+0·047	+0·021	+0·005	+1·132	−1·132	+0·000
11	−0·022	−0·100	+0·252	+0·210	+0·162	+0·106	+0·044	−0·018	−0·012	−0·010	−0·006	−0·004	−0·003	−0·001	nil	+0·774	−0·176	+0·598
10	+0·018	+0·072	+0·156	−0·570	−0·428	−0·266	−0·088	+0·098	+0·078	+0·058	+0·044	+0·028	+0·016	+0·007	+0·002	+0·577	−1·352	−0·755
9	−0·023	−0·091	−0·202	+0·284	+0·252	+0·216	+0·176	+0·134	+0·106	+0·086	+0·060	+0·040	+0·023	+0·010	+0·003	+1·390	−0·316	+1·074
8	+0·018	+0·072	+0·157	+0·276	−0·612	−0·452	−0·274	−0·092	−0·074	−0·056	−0·042	−0·026	−0·015	−0·006	−0·002	+0·523	−1·651	−1·128
7	−0·020	−0·081	−0·179	−0·314	+0·300	+0·290	+0·276	+0·260	+0·212	+0·164	+0·116	+0·078	+0·044	+0·020	+0·005	+1·765	−0·594	+1·171
6	+0·017	+0·068	+0·152	+0·264	+0·402	−0·620	−0·452	−0·274	−0·220	−0·170	−0·122	−0·082	−0·047	−0·020	−0·005	+0·903	−2·012	−1·109
5	−0·017	−0·069	−0·153	−0·266	−0·404	+0·328	+0·342	+0·356	+0·290	+0·222	+0·158	+0·104	+0·060	+0·026	+0·007	+1·893	−0·909	+0·984
4	+0·016	+0·062	+0·142	+0·242	+0·370	+0·516	−0·610	−0·446	−0·362	−0·276	−0·196	−0·130	−0·074	−0·034	−0·009	+1·348	−2·137	−0·789
3	−0·014	−0·056	−0·123	−0·216	−0·326	−0·454	+0·372	+0·420	+0·340	+0·262	+0·186	+0·124	+0·071	+0·032	+0·008	+1·815	−1·189	+0·626
2	+0·014	+0·056	+0·123	+0·214	+0·324	+0·454	+0·588	−0·600	−0·482	−0·374	−0·266	−0·178	−0·100	−0·046	−0·011	+1·773	−2·057	−0·284
1	−0·002	−0·007	−0·016	−0·030	−0·046	−0·064	−0·080	+0·900	−0·080	−0·064	−0·046	−0·030	−0·016	−0·007	−0·002	+0·900	−0·490	+0·410

Example II.

Take next this same arch as in Example I., but instead of taking it out with one ton on each apex, suppose that there are 16 tons equally distributed over the whole arch, or that it carries 0·2 ton per foot run of span. This would both alter the weights at each apex, and also the horizontal thrusts.

Working out the weights at 0·2 ton per foot run horizontally, the values of the units W and the horizontal thrusts would be as follows:—

		T_1 or T_2
W_1	0·305	0·00293
W_2	0·597	0·02276
W_3	0·872	0·07345
W_4	1·106	0·16274
W_5	1·295	0·28761
W_6	1·442	0·44522
W_7	1·53	0·61582
W_8	1·56	0·78000
W_9	1·53	0·61582
W_{10}	1·442	0·44522
W_{11}	1·295	0·28761
W_{12}	1·106	0·16274
W_{13}	0·872	0·07345
W_{14}	0·597	0·02276
W_{15}	0·305	0·00293
	Thrust T =	4·00106

Laying this thrust T down, Fig. 3, Plate III., and setting up the units of these loads vertically, as in the previous example, the diagram of strains for the arch with an equally distributed load of 16 tons is obtained; the values of which are:—

EXTRADOS.

On A	B	C	D	E	F	G	H
4·02	4·02	3·78	3·32	3·04	3·14	3·87	5·44

INTRADOS.

Q	P	O	N	M	L	K
0·38	1·42	2·82	4·16	4·96	4·74	3·14

BARS.

1	2	3	4	5	6	7	8
+0·76	−0·51	+1·12	−1·40	+1·70	−1·90	+1·92	−1·82

9	10	11	12	13	14	15	16
+1·62	−1·07	+0·74	+0·28	−0·68	+2·16	−2·34	+4·28

The above values are measured from the diagram, although they can also be arrived at by drawing a diagram for each separate load, or by taking the values in Table I. and multiplying them by their proper units for each load.

Example III.

Next proceed to take out the same arch under the same conditions as in Example I., that is with one ton on each apex, retaining the radial struts, but leaving out the diagonals in black lines, and substituting those shown in dotted lines. As in Example I. there will be the same reactions and horizontal thrusts, therefore it is needless to recapitulate them. Neither is it necessary to explain the diagram, Fig. 4, Plate II., which is similarly arrived at as in Example I., and elucidates itself, the results being tabulated in the last column of Table II.

Example IV.

Fig 5, Plate II., shows the diagram of strains for the arch with the diagonals in dotted lines, but the load equally distributed at 0·2 ton per foot run, as in Example II., and therefore the same weights and thrusts are applicable in this case; the strains being—

EXTRADOS.

On A	B	C	D	E	F	G	H
3·71	3·18	2·61	2·26	2·41	3·11	5·14	7·97

INTRADOS.

Q	P	O	N	M	L	K	J
0·0	0·38	1·42	2·82	4·16	4·96	4·74	3·14

BARS.

1	2	3	4	5	6	7	8	9
Nil	+0·51	−0·31	+1·40	−0·77	+1·90	−0·88	+1·82	−0·55

10	11	12	13	14	15	16	17
+1·07	+0·15	−0·28	+1·14	−2·16	+2·25	−4·28	+3·22

TABLE II.—Table of Strains on the Arch, Fig. 1, Plate II., with the Diagonals in Dotted Lines.

Compression +. *Tension* −.

Extrados.

	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}	W_{11}	W_{12}	W_{13}	W_{14}	W_{15}	Greatest Compression. +	Greatest Tension. −	Fully Loaded.
H	+0·995	+0·967	+0·921	+0·856	+0·764	+0·696	+0·600	+0·504	+0·404	+0·312	+0·224	+0·148	+0·085	+0·038	+0·010	..	..	+7·524
G	+0·078	+1·013	+0·923	+0·808	+0·668	+0·508	+0·332	+0·152	+0·120	+0·092	+0·066	+0·042	+0·025	+0·011	+0·003	..	..	+4·841
F	+0·069	+0·277	+1·070	+0·894	+0·680	+0·434	+0·168	−0·114	−0·092	−0·070	−0·050	−0·036	−0·020	−0·009	−0·002	+3·592	−0·393	+3·199
E	+0·058	+0·235	+0·517	+1·108	+0·814	+0·476	+0·108	−0·272	−0·224	−0·170	−0·126	−0·084	−0·049	−0·022	−0·006	+3·316	−0·953	+2·363
D	+0·048	+0·193	+0·424	+0·736	+1·068	+0·634	+0·160	−0·330	−0·270	−0·206	−0·152	−0·100	−0·058	−0·027	−0·007	+3·263	−1·150	+2·113
C	+0·038	+0·151	+0·331	+0·576	+0·872	+0·900	+0·324	−0·274	−0·228	−0·174	−0·126	−0·084	−0·048	−0·022	−0·006	+3·192	−0·962	+2·230
B	+0·027	+0·109	+0·242	+0·420	+0·634	+0·882	+0·588	−0·114	−0·096	−0·076	−0·052	−0·034	−0·020	−0·010	−0·002	+2·902	−0·404	+2·498
A	+0·018	+0·072	+0·157	+0·276	+0·414	+0·576	+0·752	+0·148	+0·118	+0·088	+0·066	+0·042	+0·026	+0·011	+0·003	..	..	+2·767

Intrados.

J	−0·086	−0·057	−0·005	+0·062	+0·142	+0·234	+0·334	+0·444	+0·356	+0·274	+0·196	+0·130	+0·074	+0·034	+0·008	+2·288	−0·148	+2·140
K	−0·074	−0·297	−0·189	−0·046	+0·128	+0·324	+0·554	+0·770	+0·618	+0·480	+0·342	+0·228	+0·131	+0·059	+0·015	+3·649	−0·606	+3·043
L	−0·061	−0·246	−0·540	−0·314	−0·040	+0·272	+0·616	+0·970	+0·784	+0·604	+0·434	+0·288	+0·166	+0·074	+0·019	+4·227	−1·201	+3·026
M	−0·048	−0·193	−0·424	−0·736	−0·356	+0·076	+0·550	+1·040	+0·838	+0·644	+0·466	+0·310	+0·177	+0·080	+0·021	+4·202	−1·757	+2·445
N	−0·035	−0·139	−0·308	−0·532	−0·810	−0·258	+0·346	+0·970	+0·786	+0·604	+0·434	+0·290	+0·166	+0·075	+0·019	+3·690	−2·082	+1·608
O	−0·022	−0·089	−0·196	−0·338	−0·512	−0·714	+0·014	+0·770	+0·624	+0·476	+0·344	+0·228	+0·131	+0·059	+0·015	+2·661	−1·871	+0·790
P	−0·010	−0·042	−0·091	−0·158	−0·238	−0·334	−0·434	+0·440	+0·354	+0·274	+0·198	+0·132	+0·074	+0·033	+0·008	+1·513	−1·307	+0·206

Bars.

17	−0·088	−0·057	−0·005	+0·064	+0·144	+0·236	+0·344	+0·450	+0·362	+0·276	+0·200	+0·134	+0·076	+0·034	+0·008	+2·328	−0·150	+2·178
16	+0·116	+0·076	+0·006	−0·084	−0·192	−0·314	−0·452	−0·596	−0·482	−0·368	−0·266	−0·176	−0·101	−0·045	−0·011	+0·198	−3·087	−2·889
15	−0·005	−0·256	−0·187	−0·096	+0·012	+0·136	+0·274	+0·456	+0·340	+0·258	+0·184	+0·126	+0·072	+0·031	+0·008	+1·897	−0·544	+1·353
14	−0·016	+0·324	+0·248	+0·144	+0·018	−0·124	−0·280	−0·446	−0·358	−0·274	−0·198	−0·132	−0·076	−0·034	−0·009	+0·734	−1·947	−1·213
13	−0·002	−0·006	−0·393	−0·278	−0·146	+0·012	+0·176	+0·356	+0·288	+0·218	+0·160	+0·104	+0·061	+0·027	+0·007	+1·409	−0·825	+0·584
12	−0·017	−0·068	+0·476	+0·362	+0·224	+0·070	−0·100	−0·274	−0·224	−0·170	−0·124	−0·082	−0·047	−0·021	−0·005	+1·132	−1·132	nil
11	+0·002	+0·006	+0·012	−0·488	−0·328	−0·146	+0·054	+0·260	+0·212	+0·162	+0·118	+0·076	+0·045	+0·019	+0·005	+0·971	−0·962	+0·009
10	−0·018	−0·072	−0·156	+0·570	+0·428	+0·266	+0·088	−0·098	−0·078	−0·058	−0·044	−0·028	−0·016	−0·007	−0·002	+1·352	−0·577	+0·775
9	+0·004	+0·017	+0·036	+0·066	−0·530	−0·326	−0·098	+0·136	+0·112	+0·086	+0·064	+0·040	+0·023	+0·010	+0·002	+0·596	−0·954	−0·358
8	−0·018	−0·072	−0·157	−0·276	+0·612	+0·452	+0·274	+0·092	+0·074	+0·056	+0·042	+0·026	+0·015	+0·006	+0·002	+1·651	−0·523	+1·128
7	+0·006	+0·024	+0·053	+0·098	+0·140	−0·518	−0·272	−0·014	−0·010	−0·008	−0·006	−0·003	−0·002	nil	nil	+0·321	−0·833	−0·512
6	−0·017	−0·068	−0·152	−0·264	−0·402	+0·620	+0·452	+0·274	+0·220	+0·170	−0·122	+0·082	+0·047	+0·020	+0·005	+2·012	−0·903	+1·109
5	+0·008	+0·029	+0·067	+0·118	+0·176	+0·246	−0·458	−0·188	−0·148	−0·114	−0·082	−0·054	−0·020	−0·009	−0·003	+0·644	−1·076	−0·432
4	−0·016	−0·062	−0·142	−0·242	−0·370	−0·516	+0·610	+0·446	+0·362	+0·276	+0·196	+0·130	+0·074	+0·034	+0·009	+2·137	−1·348	+0·789
3	+0·009	+0·033	+0·075	+0·128	+0·198	+0·274	+0·358	−0·366	−0·294	−0·228	−0·162	−0·106	−0·059	−0·027	−0·007	+1·075	−1·249	−0·174
2	−0·014	−0·056	−0·123	−0·214	−0·324	−0·454	−0·588	+0·600	+0·482	+0·374	+0·266	+0·178	+0·100	+0·046	+0·011	+2·057	−1·773	+0·284

Now in Examples II. and IV. are given the strains for two similar arches, each loaded with 16 tons equally distributed, or with 0·2 ton per foot of span, but with different *diagonal* bracing; in Example II. the diagonals in black lines were taken, in Example IV. those in dotted lines. Then to get the strains on this arch shown, Fig. 1, Plate II., loaded equally with 16 tons and doubly braced, add together the results obtained in Examples II. and IV., and divide the results by two, which can be written down thus:—

EXTRADOS.

	A	B	C	D	E	F	G	H
Ex. 2.	4·02	4·02	3·73	3·32	3·04	3·14	3·87	5·44
Ex. 4.	3·71	3·18	2·61	2·26	2·41	3·11	5·14	7·97
+ 2	7·73	7·20	6·14	5·58	5·45	6·25	9·01	13·41
	3·86	3·60	3·07	2·79	2·72	3·12	4·50	6·70

INTRADOS.

	Q	P	O	N	M	L	K	J
Ex. 2.	0·38	1·42	2·82	4·16	4·96	4·74	3·14	Nil
Ex. 4.	Nil	0·38	1·42	2·82	4·16	4·96	4·74	3·14
+ 2	0·38	1·80	4·24	6·98	9·12	9·70	7·88	3·14
	0·19	0·90	2·12	3·49	4·56	4·85	3·94	1·57

BARS.

	1	2	3	4	5	6	7	8	9
Ex. 2.	+0·76	−0·51	+1·12	−1·40	+1·70	−1·90	+1·92	−1·82	+1·62
Ex. 4.	Nil	+0·51	−0·31	+1·40	−0·77	+1·90	−0·88	+1·82	−0·55
+ 2	+0·76	∓0·51	+0·81	∓1·40	+0·93	∓1·90	+1·04	∓1·82	+1·07
Black lines		−0·25		−0·70		−0·95		−0·91	
Radials	+0·38		+0·40		+0·46		+0·52		+0·53
Dotted lines		+0·25		+0·70		+0·95		+0·91	

	10	11	12	13	14	15	16	17
Ex. 2.	−1·07	+0·74	+0·28	−0·68	+2·16	−2·34	+4·28	Nil
Ex. 4.	+1·07	+0·15	−0·28	+1·14	−2·16	+2·25	−4·28	+3·22
+ 2	∓1·07	+0·89	±0·28	+0·46	±2·16	−0·09	±4·28	+3·22
Black lines	−0·53		+0·14		+1·08		+2·14	
Radials		+0·44		+0·23		−0·04		−1·61
Dotted lines	+0·53		−0·14		−1·08		−2·14	

It will be noticed, by looking at Tables I. and II., and also the results above obtained for the arch equally loaded, that in taking out the arch with the diagonals in black lines, as in Examples I. and II., the bars J and 17 are superfluous bars, whereas in the arch, as in Examples III. and IV., with the dotted diagonals, the bars 1 and A are superfluous bars. It will also be noticed, by the above tabulated strains on the bars, by comparing Tables I. and II., that the diagonals in each bay get the same strain, except with a different sign.

Having obtained the above results, and analysing the same, there is for the strain on the bar H of the extrados at the crown 3·86 tons, and on Q, in the intrados, 0·19 ton; these two values added together give 4·05 tons thrust or strain at the crown of the arch.

Now apply the formula $\frac{W L}{8 D}$, that all mathematical authorities give for the thrust or strain at the crown of an iron arch equally loaded, substituting values $\frac{80 \times 16}{8 \times 40} = 4$ tons, which checks with the value given above, as it must be remembered that the bars are slightly inclined in the example of the arch given.

Again, suppose the extrados of this arch be taken and transformed into a bowstring girder, as shown Fig. 5, Plate I., substituting a tie for the thrust of the abutments, and introducing diagonal bracing to supply the stiffness, and working out the strains with one ton on each apex in the ordinary way by Maxwell's diagrams, Fig. 6, Plate I., it will be found that the polygon of forces turns on the same horizontal thrust as in the arch, *i.e.*, 2·92525 tons. Also that if it is assumed that the bowstring is loaded uniformly with 0·2 ton per foot run of span, the units would be the same at each apex as for the arch in Example II.; working this out with these units by Maxwell's diagram, Fig. 7, Plate I., as before, it will be found that the polygons turn on the horizontal thrust of 4·05 tons as in the arch.

However, to prove that both the theory and results

obtained are correct, turn to the diagrams for each separate load from which the tables have been compiled, and which are shown in Plate III. Figs. 1 to 8 representing the strains for the load of one ton on each apex, as in Example I., with diagonals in black lines, and Figs. 9 to 16 those for the load of one ton on each apex, as in Example III., with diagonals in dotted lines, the letters on the diagram corresponding with those on Fig. 1, Plate II.

In all the tables the entire table has not been carried out, as it is evident that taking, say the load W_3, this load would give the same strain on all the bars between it and R_2, as the weight W_{13} would give between it and R_1. Similarly with the diagrams for each separate load, it is only necessary to take those for one side, as the corresponding load on the other side of the arch would give the same diagram only upside down.

As an example of working out these diagrams for the separate loads as shown on Plate III., take any load, say $W_6 = 1$ ton on that point, with the diagonals in black lines, as in Example I., Fig. 1, Plate II. Referring to page 10 it is found that the horizontal thrust for this load is $T = 0{\cdot}30875$; lay this down horizontally to any scale of parts as shown by $x\ y$, Fig. 6, Plate III.; then it is also seen at page 10 that the two reactions are respectively $R_1 = 0{\cdot}69125$ and $R_2 = 0{\cdot}30875$; lay these off vertically from y, as shown by $y\ z$ and $y\ v$ in the diagram. There are now the three points v, x, z, to work from, all the strains for the bars of the extrados being measured from v and z, and those of the intrados from the point x.

Commence by drawing down from the point Z the line H parallel to the bar H in the complete sketch of the arch, and from the point x draw the line 16 parallel to the diagonal 16 in the sketch until they intersect; measuring from this intersection to the point Z gives the strain on H, and measuring from intersection to the point x gives the strain on the diagonal 16. Then from this intersection draw 15 parallel to the radial 15 in sketch, and from x draw the line K parallel to the line K in the intrados of the arch until it intersects 15;

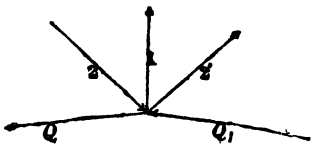
measuring these two lines will give the strains on 15 and K; from this last intersection draw the line 14 parallel to the diagonal 14 on sketch, and from Z draw the line G parallel to the bar G of the extrados until they intersect; measuring these two lines will give the strains on G and the diagonal 14; and so on until the complete figure of polygons for the whole arch is completed, the values of which are tabulated in Table I. The diagram might just as readily have been commenced from the point *v* in the same manner for the other side of the arch.

The diagrams have in all cases been lettered and figured as far as practicable, but some of the letters and figures have necessarily been omitted where the smallness of the figure did not admit of their being inserted; however, every endeavour has been made to ensure clearness.

Now taking the results as tabulated for this diagram for the load W_6 from Table I., and writing them down on a complete sketch of the arch, they must fulfil the requirements necessary for the stability of any structure, viz., *that all the forces or strains acting about any point in the structure or polygon shall keep that point in equilibrium.*

Suppose any point be taken to see whether these conditions are fulfilled. Say the point at the crown of the intrados. Here we have five forces, Q, 1, and 2′ tension, and 2 and Q_1 compression, as shown Fig. 3.

Fig. 3.



If the direction of 2 and Q_1 be retained, but transferred to the other side of the point, this would make them tensions, which would come to the same thing, and would give five tensions acting on the point. Suppose this be done, and

giving each their proper values, as shown, Fig. 4. Resolving Q and Q_1 the resultant x is obtained; resolving 1 and 2' the resultant y is obtained, and resolving these two resultants x and y the resultant Z is obtained; which is equal and opposite to the force 2, and therefore the point is kept in equilibrium by two equal and opposite forces.

Fig. 4.

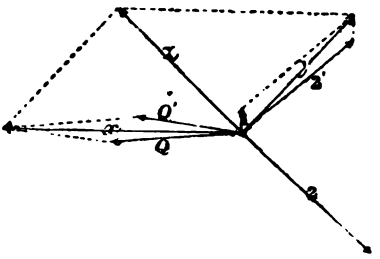


Fig. 5.

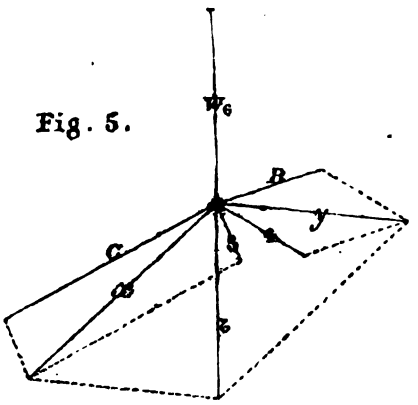
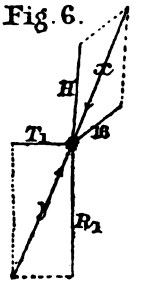


Fig. 6.

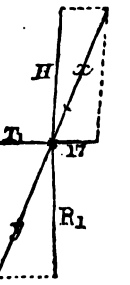


Suppose the point where the weight itself is applied is taken next; here there are five compression strains as shown, Fig. 5. Lay these down to their proper directions and magnitudes, resolving C and 5 the resultant x is obtained; resolving B and 4 the resultant y is obtained; and resolving these two the resultant Z is obtained, equal and opposite in direction to the weight W_6, therefore this point is in equilibrium. Again, take the point R_1 at the abutment, Fig. 6 here are four compression forces. The force H in the

extrados, the diagonal 16, the reaction R_1 for this load, and horizontal thrust T_1 for the same, laying these down as shown in Fig. 6 to their proper directions and magnitudes, the two opposite and equal resultants x and y are obtained, as shown in the figure.

It has now been shown how to test the strain at any point of the polygon or arch, with the diagonals in black lines, but it may be as well to show how the figure works out for the point last taken, R_1 in the arch braced with the dotted diagonals, Table II.; take the same load W_6, and at the point R_1 there are four compressive forces; lay these down to their proper directions and values, Fig. 7, there result as before the two opposite and equal resultants x and y. Any other point can be tested in the same manner.

Fig 7.



Example V.

In this example the same span, 80 feet out to out, will be taken for a semicircular arch, Fig. 1, Plate IV., and, as in the previous examples, loaded with 1 ton on each apex, doubly latticed, but with the radials omitted.

First take the arch as shown by the lines in black, Fig. 1, Plate IV. Here there are the same horizontal thrusts and reactions for each weight as in the previous cases, which can be written thus:—

	T_1 or T_2	R_1	R_2
W_2	0·038125	0·961875	0·038125
W_4	0·147125	0·852875	0·147125
W_6	0·30875	0·69125	0·30875
W_8	0·5	0·5	0·5
W_{10}	0·30875	0·30875	0·69125
W_{12}	0·147125	0·147125	0·852875
W_{14}	0·038125	0·038125	0·961875
$T = 1·488$			

Lay this thrust horizontally down, Fig. 2, Plate IV., as was done in the previous examples, and lay off the weights vertically. Then, proceeding in the same manner as before

by Maxwell's diagrams, the polygon of forces is obtained as shown. These results are tabulated in Table III., and were arrived at by taking out the diagram for each separate weight; and an example as to constructing them is given by Fig. 3, Plate IV., for the weight W_4, which will be readily understood from the figure.

This diagram is commenced, having the same three points as before to start from, by drawing down the line D parallel to the bar D in the extrados in sketch, until it intersects the line 8, drawn parallel to the diagonal 8 in sketch, from the horizontal thrust, and then proceeding as explained in the previous example.

Now an arch of this description built of iron would rarely be used, except in the case of a roof; and as the only disturbing forces likely to occur to such a structure to strain it unequally would be either snow or wind on one side, or both together on the same side, it is needless in practice to go to the trouble and time to take each load out separately. Therefore if one diagram be taken out for the roof equally loaded, that is for its own weight, and another for when only loaded on one side, adding the two together the result will give the maximum strains which it is necessary to provide against in the metal.

To draw this diagram, which is shown by Fig. 4, Plate IV., proceed as follows. Obtain the horizontal thrust and reactions for the weights of 1 ton at each apex on one side; thus,

	T_1 or T_2	R_1	R_2
W_2	0·038125	0·961875	0·038125
W_4	0·147125	0·852875	0·147125
W_6	0·30875	0·69125	0·30875
W_8	0·5	0·5	0·5
	$T = 0·994$	$R_1 = 3·006$	$R_2 = 0·994$

Lay this horizontal thrust down with the reactions on each side vertically to it, as shown in the figure, then as the sum of the weights must equal the sum of the reactions, lay these off within them. Then all the points necessary for forming the polygon of forces are obtained, as explained by

TABLE III.

TABLE of the STRAINS on the ARCH, Fig. 1, Plate IV., as SHOWN by the LINES in BLACK.

Compression +. *Tension* −.

EXTRADOS.

	W_2	W_4	W_6	W_8	W_{10}	W_{12}	W_{14}	Greatest Compression. +	Greatest Tension. −	Fully Loaded.	Half Loaded with W_2, W_4, W_6, and W_8.		
D	+1·113	+0·892	+0·558	+0·164	+0·100	+0·048	+0·014	..	..	+2·889	+2·727	+0·326	D_1
C	+0·257	+1·218	+0·524	−0·306	−0·192	−0·096	−0·023	+1·999	−0·617	+1·382	+1·693	−0·617	C_1
B	+0·166	+0·632	+0·968	−0·306	−0·192	−0·096	−0·023	+1·766	−0·617	+1·149	+1·460	−0·617	B_1
A	+0·077	+0·302	+0·632	+0·164	+0·100	+0·048	+0·014	..	..	+1·337	+1·175	+0·326	A_1
						INTRADOS.							
E	−0·272	−0·042	+0·302	+0·712	+0·440	+0·210	+0·053	+1·717	−0·314	+1·403	+0·700	+1·415	E_1
F	−0·176	−0·680	+0·072	+0·962	+0·596	+0·286	+0·074	+1·990	−0·856	+1·134	+0·178	+1·918	F_1
G	−0·081	−0·314	−0·660	+0·712	+0·440	+0·210	+0·053	+1·415	−1·055	−0·360	−0·343	+1·415	G_1
						BARS.							
8	−0·219	−0·034	+0·246	+0·576	+0·355	+0·170	+0·044	+1·391	−0·253	+1·138	+0·569	+1·145	8^1
7	+0·144	+0·020	−0·158	−0·376	−0·232	−0·112	−0·028	+0·164	−0·906	−0·742	−0·370	−0·748	7^1
6	nil	−0·524	−0·100	+0·410	+0·254	+0·122	+0·031	+0·817	−0·624	+0·193	−0·214	+0·817	6^1
5	−0·128	+0·324	+0·208	+0·076	+0·044	+0·022	+0·004	+0·678	−0·128	+0·550	+0·480	+0·146	5^1
4	+0·025	+0·098	−0·572	+0·076	+0·044	+0·022	+0·004	+0·269	−0·572	−0·303	−0·373	+0·146	4^1
3	−0·102	−0·390	+0·404	+0·410	+0·254	+0·122	+0·031	+1·221	−0·492	+0·729	+0·322	+0·817	3^1
2	+0·042	+0·164	+0·346	−0·376	−0·232	−0·112	−0·028	+0·552	−0·748	−0·196	+0·176	−0·748	2^1
1	−0·066	−0·254	−0·534	+0·576	+0·355	+0·170	+0·044	+1·145	−0·854	+0·291	−0·278	+1·145	1^1

the figure, which results agree with those tabulated in the two last columns of Table III., and which were arrived at by the addition of the values for each separate load.

Fig. 5, Plate IV., represents the strains for this arch equally loaded, that is, with 0·1 per foot run of span. This will slightly vary both the weight at each point and the horizontal thrusts from those in Examples II. and IV.; they may be written down thus:—

	T_1 or T_2
$W_2 = 0{\cdot}5885$ ton.	0·0225
$W_4 = 1{\cdot}0825$,,	0·1592
$W_6 = 1{\cdot}4115$,,	0·4358
$W_8 = 1{\cdot}53$,,	0·765
$W_{10} = 1{\cdot}4115$,,	0·4358
$W_{12} = 1{\cdot}0825$,,	0·1592
$W_{14} = 0{\cdot}5885$,,	0·0225
	T = 2·0000

Laying this down, and setting up the above units to scale, the following values are given by scaling the figures:—

Extrados.

D	C	B	A
+2·83	+1·33	+1·28	+1·72

Intrados.

E	F	G
+2·21	+1·96	+0·66

Bars.

8	7	6	5	4	3	2	1
+1·80	−1·15	+0·43	+0·77	−0·47	+1·24	−0·34	+0·54

No strain passes through the centre of intrados, as the arch would be perfectly stable, when equally loaded, with this system of bracing, if assumed to be hinged at the crown.

Example VI.

In the last example the arch as shown in black lines was dealt with, Fig. 1, Plate IV. This same arch, but as shown by the dotted lines, will now be considered. In the same manner as before it will be assumed as loaded at each

apex with 1 ton, and the horizontal thrusts and reactions will be

	T_1 or T_2	R_1	R_2
W_1	0·009625	0·990375	0·009625
W_3	0·08425	0·91575	0·08425
W_5	0·22225	0·77775	0·22225
W_7	0·4025	0·5975	0·4025
W_9	0·4025	0·4025	0·5975
W_{11}	0·22225	0·22225	0·77775
W_{13}	0·08425	0·08425	0·91575
W_{15}	0·009625	0·009625	0·990375
	T = 1·437250		

Laying this thrust down as before, Fig. 6, Plate IV., the strains for this arch, loaded on each apex with 1 ton, are obtained, which results are tabulated in Table IV. These results, however, were obtained by separate diagrams for each load, and the method of constructing them is shown by Fig. 7, Plate IV. It will be observed that for each triangulation it alters the way in which the diagram of polygons commences, for in this, as in the previous Example V., there are the same three points to work from, but for this triangulation one commences by drawing down the line M parallel to the bar M in the extrados of the arch, until it intersects the horizontal bar 9 of the arch, and then the polygon is continued from this intersection. It will be observed that in this case the polygon of forces does not turn exactly on the horizontal thrust, and the reason will be evident by examining Fig. 6, Plate III., wherein, if the vertical 1 were left out, the diagonals 2 and 2′ would meet a little to the left of the horizontal thrust.

As in the previous example this arch, loaded on one side only, will next be taken, with 1 ton on each apex. To draw this diagram, which is shown, Fig. 8, Plate IV., proceed as before to get the horizontal thrust and reactions.

	T_1 or T_2	R_1	R_2
W_1	0·009625	0·990375	0·009625
W_3	0·08425	0·91575	0·08425
W_5	0·22225	0·77775	0·22225
W_7	0·4025	0·5975	0·4025
	T = 0·718625	3·281375	0·718625

TABLE IV.

TABLE of STRAINS on the ARCH, Fig. 1, Plate IV., as SHOWN by the DOTTED LINES.

Compression +. *Tension* −.

EXTRADOS.

	W_1	W_3	W_5	W_7	W_9	W_{11}	W_{13}	W_{15}	Greatest Compression. +	Greatest Tension. −	Fully Loaded.	Half Loaded with W_1, 3, 5, 7.		
M	+0·995	+0·921	+0·784	+0·600	+0·406	+0·224	+0·086	+0·009	..	..	+4·025	+3·300	+0·725	M_1
L	+0·076	+1·179	+0·748	+0·178	−0·106	−0·058	−0·023	−0·003	+2·181	−0·190	+1·991	+2·181	−0·190	L_1
K	+0·053	+0·467	+1·176	+0·178	−0·300	−0·166	−0·065	−0·008	+1·874	−0·539	+1·335	+1·874	−0·539	K_1
J	+0·030	+0·267	+0·702	+0·646	−0·106	−0·058	−0·023	−0·003	+1·645	−0·190	+1·455	+1·645	−0·190	J_1
I	+0·010	+0·093	+0·246	+0·444	+0·444	+0·246	+0·093	+0·010	..	..	+1·586	+0·793	..	

INTRADOS.

N	−0·080	−0·004	+0·134	+0·312	+0·330	+0·180	+0·069	+0·008	+1·033	−0·084	+0·949	+0·362	+0·587	N_1
O	−0·057	−0·499	−0·038	+0·574	+0·730	+0·402	+0·154	+0·018	+1·878	−0·594	+1·284	−0·020	+1·304	O_1
P	−0·032	−0·284	−0·752	+0·320	+0·730	+0·402	+0·154	+0·018	+1·624	−1·068	+0·556	−0·748	+1·304	P_1
Q	−0·010	−0·086	−0·224	−0·400	+0·330	+0·180	+0·069	+0·008	+0·587	−0·720	−0·133	−0·720	+0·587	Q_1

BARS.

9	−0·088	−0·004	+0·144	+0·344	+0·364	+0·198	+0·077	+0·008	+1·135	−0·092	+1·043	+0·396	+0·647	9^1
8	+0·106	+0·005	−0·178	−0·418	−0·446	−0·244	−0·092	−0·011	+0·111	−1·389	−1·278	−0·485	−0·793	8^1
7	−0·007	−0·402	−0·098	+0·302	+0·420	+0·232	+0·088	+0·010	+1·052	−0·507	+0·545	−0·205	+0·750	7^1
6	−0·034	+0·259	+0·128	−0·046	−0·114	−0·064	−0·024	−0·003	+0·387	−0·285	+0·102	+0·307	−0·205	6^1
5	+0·004	+0·029	−0·590	−0·038	+0·206	+0·116	+0·044	+0·005	+0·404	−0·628	−0·224	−0·595	+0·371	5^1
4	−0·029	−0·257	+0·364	+0·296	+0·204	+0·114	+0·044	+0·005	+1·027	−0·286	+0·741	+0·374	+0·367	4^1
3	+0·009	+0·078	+0·210	−0·494	−0·110	−0·064	−0·024	−0·003	+0·297	−0·695	−0·398	−0·197	−0·201	3^1
2	−0·021	−0·186	−0·494	+0·474	+0·420	+0·232	+0·088	+0·010	+1·224	−0·701	+0·523	−0·227	+0·750	2^1
1	+0·012	+0·101	+0·264	+0·480	−0·498	−0·274	−0·106	−0·012	+0·857	−0·890	−0·033	+0·857	−0·890	1^1

Lay this down, and, as before, laying off the reactions vertically with the weights laid off between them. Draw the polygon of forces as shown in Fig. 8, which results agree with those tabulated in the two last columns of Table IV., and which were arrived at by addition of Tables.

Fig. 9, Plate IV., represents the strains for the arch loaded equally with 0·1 ton per foot run of span, and as in this arch the loads will vary slightly from those in Examples II. and IV., write them down thus:—

		T_1 or T_2
W_1	0·0370 ton.	0·00328
W_3	0·8505 ,,	0·07165
W_5	1·273 ,,	0·28292
W_7	1·501 ,,	0·60415
W_9	1·501 ,,	0·60415
W_{11}	1·273 ,,	0·28292
W_{13}	0·8505 ,,	0·07165
W_{15}	0·3370 ,,	0·00328
	T =	1·92400

Laying this down, and setting up the units as explained in the previous examples. The strains which are scaled from the diagram as below.

EXTRADOS.

M	L	K	J	I
+3·93	+2·01	+1·43	+1·86	+2·14

INTRADOS.

N	O	P	Q
+1·39	+2·09	+0·99	−0·18

BARS.

9	8	7	6	5	4	3	2	1
+1·54	−1·86	+0·97	+0·03	−0·28	+1·18	−0·67	+0·91	−0·06

Here are now the strains on two similar arches but with different bracing; therefore if the two results are added together the addition will give the strains on an arch with double diagonal bracing, and equally loaded with 0·2 ton per foot run, and the results would stand thus:—

EXTRADOS.

D+M	D+L	C+L	C+K	B+K	B+J	A+J	A+I
2·83	2·83	1·33	1·33	1·28	1·28	1·72	1·72
3·93	2·01	2·01	1·43	1·43	1·86	1·86	2·14
6·76	4·84	3·34	2·76	2·71	3·14	3·58	3·86

INTRADOS.

N	E+N	E+O	F+O	F+P	G+P	G+Q	Q
	2·21	2·21	1·96	1·96	0·66	0·66	
1·39	1·39	2·09	2·09	0·99	0·99	−0·18	−0·18
+1·39	+3·60	+4·30	+4·05	+2·95	−1·65	+0·48	−0·18

BARS.

	9	8	7	6	5	4	3	2	1
Black lines		+1·80	−1·15	+0·43	+0·77	−0·47	+1·24	−0·34	+0·54
Dotted „	+1·54	−1·86	+0·97	+0·03	−0·28	+1·18	−0·67	+0·91	−0·06

In the foregoing examples of the arch it will doubtless have been noticed how, in the diagrams for each separate load, the figure of polygons for the strains on each side of the centre of the arch always turn on the horizontal thrust, or on the line vertically drawn through it; but the same thing, it will be remembered, occurs in the bowstring girder, as shown by Fig. 3, Plate I., and it is this very fact which enables one to see, directly the drawing of the figure of the polygons has progressed so far, whether the figure has been commenced in the proper manner; for if it does not turn on the horizontal thrust, some error must have been made in the values of the horizontal thrust, reactions, starting the figures, or its setting out. There is only one case in which the polygon of forces does not turn exactly in a line with the horizontal thrust, and attention was drawn to it at the time; this is in the case of the arch shown in dotted lines, Fig. 1, Plate IV. By looking at the example, Fig. 7 in same Plate, for the single load W_5, the point of junction of the bars 1 and 1′ is not directly underneath the horizontal thrust, and the reason of this will be evident by referring to Fig. 6, Plate III., or any of the Figs. from 1 to 8, where it will be seen, by looking at these diagrams, that if the vertical 1 were removed, the strain on the bar 2 would be reduced, and that on 2′ increased, and A and A_1 would merge into one horizontal bar.

A departure has been made in this treatise from the usual practice in engineering works, and that is in taking the arch before the bridge, but the reason for doing so will be evident, that once having proved the strains on an arch proper, the

strains on an arched girder or bridge follows as a natural consequence therefrom, as will be seen in the following pages.

Although many other types of arches could have been given, still sufficient data has been furnished whereby the strains on any other types can be arrived at.

Taking Examples I., II., III., and IV., it is seen that, however the weight is distributed, the strains on the diagonals are equal; suppose Fig. 1, Plate II., be turned to, and look upon the eight divisions on each side as representing the voussoirs of a stone arch, these diagonal strains would represent the transverse strains through each voussoir, and the strains on the radials as the friction at their joints.

CHAPTER II.

THE ARCH BRIDGE.

Example I.

Take, for example, an arched bridge, Fig. 1, Plate V., 80 feet span, 8 feet rise, or versed sine, and 2 feet deep at crown, divided into 16 bays and braced as shown in the figure. Loaded with 1 ton per foot run, this would give 5 tons collected at each apex = W, and 2·5 tons = $\frac{W}{2}$ going straight on to the abutments down bars 17 and 17'.

Proceed then similarly as in the arch proper, first to find the horizontal thrusts by the formula $\frac{W\,(a-b)}{2\,r}$, and the reactions at the abutments for each load, which may be written thus:—

	T_1 or T_2	R_1	R_2
W_1	1·25	4·6875	0·3125
W_2	2·50	4·375	0·625
W_3	3·75	4·0625	0·9375
W_4	5·00	3·75	1·250
W_5	6·25	3·4375	1·5625
W_6	7·50	3·125	1·875
W_7	8·75	2·8125	2·1875
W_8	10·00	2·50	2·50
W_9	8·75	2·1875	2·8125
W_{10}	7·50	1·875	3·125
W_{11}	6·25	1·5625	3·4375
W_{12}	5·00	1·250	3·75
W_{13}	3·75	0·9375	4·0625
W_{14}	2·50	0·625	4·375
W_{15}	1·25	0·3125	4·6875
$T =$	80·00		

Having obtained this thrust, proceed in the same manner as for the arch, by laying this horizontally down to any scale of parts, and setting off the units of load vertically to it, then working out the polygon of forces by Maxwell's diagrams, the strains on the arch when fully and equally loaded are obtained. These results are tabulated in Table V. in the last column, but the body of the Table is the result of taking the diagrams out for each load separately, and these are shown on Plate VI., Figs. 1 to 8.

Now, referring to Plate I., Fig. 2, there was given an example of a bowstring girder with the same span and the same depth virtually as the arch in this example, and both girder and arch turn on the same horizontal thrust, which bears out what was stated in the commencement, p. 9.

Turn now to Plate VI., these diagrams are constructed similarly to those for the arch. Take the diagram, Fig. 7, for the load W_7 referring to the thrusts given above its value is found to be 8·75; laying this down horizontally to any scale of parts, and laying the reactions 2·8125 and 2·1875 vertically to it, the three points x y z are obtained to work from as in the arch. All the strains for the top boom being measured from the points y and z, and all those for the arch being measured from the point x.

All strains lying to the left of y and z are compressive, those lying to the right being tensile for the top boom, and all strains lying to the right of x are compressive, and those to the left tensile for the arch.

Then, commencing from the points obtained, proceed by drawing J from the point X parallel to the bar J in the sketch, Fig. 1, Plate V., of the bridge girder, and from the point Z draw the line 17 parallel to the same bar on sketch; measuring from this intersection to the point X gives the strain on J, and measuring to Z gives the strain on bar 17. Now in a girder of this kind the top boom is a straight line, therefore there are no distinctive bars at different angles to guide one, but the method is the same, and the values must be measured accordingly. Next, from the above point of intersection draw the line 16 parallel to the same bar on sketch, until it intersects the horizontal line drawn through Z;

TABLE V.—Table of the Arched Bridge, Fig. 1, Plate V.

Compression +. *Tension* −.

Bars.

	$\frac{W}{2}$	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}	W_{11}	W_{12}	W_{13}	W_{14}	W_{15}	$\frac{W}{2}$	Greatest Compression +	Greatest Tension −	Fully Loaded.
17	+2·50	+4·20	+3·80	+2·60	+ 1·82	+ 1·00	+ 0·20	− 0·56	− 1·35	− 1·20	−1·02	−0·85	−0·70	−0·53	−0·34	−0·17	nil	+16·12	− 6·71	+ 9·41
16	..	−4·95	−4·02	−3·07	− 2·15	− 1·20	− 0·30	+ 0·65	+ 1·60	+ 1·42	+1·20	+1·02	+0·80	+0·62	+0·40	+0·21	..	+ 7·92	−15·69	− 7·77
15	..	+5·12	+4·26	+3·37	+ 2·50	+ 1·60	+ 0·70	− 0·16	− 1·07	− 0·92	−0·81	−0·66	−0·55	−0·40	−0·27	−0·12	..	+17·55	− 4·96	+12·59
14	..	−0·17	−5·37	−4·27	− 3·15	− 2·00	− 0·90	+ 0·21	+ 1·35	+ 1·17	+1·02	+0·85	+0·62	+0·50	+0·34	+0·17	..	+ 6·23	−15·86	− 9·63
13	..	+0·09	+5·17	+4·20	+ 3·25	+ 2·22	+ 1·27	+ 0·30	− 0·72	− 0·62	−0·52	−0·42	−0·32	−0·27	−0·17	−0·09	..	+16·50	− 3·13	+13·37
12	..	−0·11	−0·24	−5·90	− 4·52	− 3·12	− 1·77	− 0·41	+ 1·00	+ 0·87	+0·75	+0·60	+0·50	+0·40	+0·24	+0·11	..	+ 4·47	−16·07	−11·60
11	..	+0·02	+0·05	+5·10	+ 4·02	+ 2·95	+ 1·90	+ 0·82	− 0·27	− 0·22	−0·17	−0·15	−0·12	−0·10	−0·05	−0·02	..	+14·86	− 1·10	+13·76
10	..	−0·05	−0·10	−0·15	− 6·52	− 4·75	− 3·05	− 1·32	+ 0·49	+ 0·35	+0·30	+0·25	+0·20	+0·15	+0·10	+0·05	..	+ 1·80	−15·94	−14·14
9	..	−0·05	−0·10	−0·15	+ 4·80	+ 3·70	+ 2·60	+ 1·50	+ 0·40	+ 0·35	+0·30	+0·25	+0·20	+0·15	+0·10	+0·05	..	+14·40	− 0·30	+14·10
8	..	+0·07	+0·19	+0·28	+ 0·37	− 7·00	− 4·92	− 2·81	− 0·75	− 0·66	−0·57	−0·46	−0·37	−0·28	−0·19	−0·07	..	+ 0·91	−18·08	−17·17
7	..	−0·12	−0·26	−0·40	− 0·50	+ 4·35	+ 3·27	+ 2·15	+ 1·02	+ 0·90	+0·77	+0·62	+0·50	+0·40	+0·26	+0·12	..	+14·36	− 1·28	+13·08
6	..	+0·28	+0·57	+0·90	+ 1·15	+ 1·42	− 7·25	− 4·80	− 2·31	− 1·97	−1·72	−1·42	−1·15	−0·90	−0·57	−0·28	..	+ 4·32	−22·37	−18·05
5	..	−0·21	−0·44	−0·35	− 0·87	− 1·10	+ 3·70	+ 2·72	+ 1·75	+ 1·53	+1·31	+1·10	+0·87	+0·65	+0·44	+0·21	..	+14·28	− 3·27	+11·01
4	..	+0·55	+1·09	+1·65	+ 2·22	+ 2·77	+ 3·32	− 6·85	− 4·50	− 3·91	−3·32	−2·77	−2·22	−1·65	−1·09	−0·55	..	+11·60	−26·86	−15·26
3	..	−0·28	−0·58	−0·90	− 1·17	− 1·47	− 1·75	+ 2·95	+ 2·35	+ 2·05	+1·75	+1·47	+1·17	+0·90	+0·58	+0·28	..	+13·50	− 6·15	+ 7·35
2	..	+0·78	+1·57	+2·35	+ 3·15	+ 3·95	+ 4·80	+ 5·45	− 6·30	− 5·45	−4·80	−3·95	−3·15	−2·35	−1·57	−0·78	..	+22·05	−28·35	− 6·30
1	..	nil	nil	nil	nil	nil	nil	nil	+ 5·00	nil	nil	nil	nil	nil	nil	nil	..	..	..	+ 5·00

Top Boom.

H	..	+2·62	+2·12	+1·62	+ 1·15	+ 0·66	+ 0·17	− 0·35	− 0·85	− 0·75	−0·65	−0·53	−0·42	−0·32	−0·21	−0·09	..	+ 8·34	− 4·17	+ 4·17
G	..	+2·71	+5·41	+4·27	+ 3·07	+ 1·87	+ 0·72	− 0·50	− 1·68	− 1·45	−1·27	−1·05	−0·85	−0·62	−0·42	−0·21	..	+18·05	− 8·05	+10·00
F	..	+2·80	+5·57	+8·40	+ 6·22	+ 4·07	+ 1·96	− 0·20	− 2·41	− 2·05	−1·80	−1·47	−1·17	−0·90	−0·58	−0·30	..	+29·02	−10·88	+18·14
E	..	+2·81	+5·65	+8·52	+11·35	+ 7·80	+ 4·35	+ 0·82	− 2·72	− 2·35	−2·05	−1·67	−1·35	−1·02	−0·67	−0·34	..	+41·30	−12·17	+29·13
D	..	+2·77	+5·50	+8·25	+11·00	+13·80	+ 8·55	+ 3·22	− 2·06	− 1·77	−1·55	−1·28	−1·04	−0·77	−0·52	−0·26	..	+53·09	− 9·25	+43·84
C	..	+2·50	+4·97	+7·97	+ 9·97	+12·47	+15·00	+ 7·50	nil	nil	nil	nil	nil	nil	nil	nil	..	..	..	+60·38
B	..	+2·23	+3·97	+5·92	+ 7·95	+ 9·92	+11·95	+13·80	+ 4·15	+ 3·60	+3·07	+2·55	+2·06	+1·50	+1·02	+0·52	..	..	..	+74·21
A	..	+1·25	+2·50	+3·75	+ 5·00	+ 6·25	+ 7·50	+ 8·75	+10·00	+ 8·75	+7·50	+6·25	+5·00	+3·75	+2·50	+1·25	..	..	..	+80·00

Arch.

J	..	+1·37	+2·67	+4·05	+ 5·37	+ 6·70	+ 8·05	+ 9·40	+10·72	+ 9·40	+8·05	+6·70	+5·37	+4·05	+2·67	+1·37	..	..	..	+85·94
K	..	−1·42	+1·42	+2·22	+ 4·07	+ 5·90	+ 7·72	+ 9·60	+11·45	+10·00	+8·57	+7·15	+5·72	+4·80	+1·42	+1·42	..	+81·46	− 1·42	+80·04
L	..	−1·51	−3·02	−0·55	+ 2·00	+ 4·52	+ 7·02	+ 9·60	+12·12	+10·60	+9·10	+7·60	+6·06	+4·55	+3·02	+1·51	..	+77·70	− 5·08	+72·62
M	..	−1·61	−3·16	−4·75	− 1·25	+ 2·25	+ 5·56	+ 9·20	+12·72	+11·07	+9·52	+7·95	+6·35	+4·75	+3·16	+1·61	..	+74·14	−10·77	+63·37
N	..	−1·61	−3·17	−4·82	− 6·45	− 1·57	+ 3·20	+ 8·07	+12·90	+11·22	+9·67	+8·05	+6·45	+4·82	+3·17	+1·61	..	+69·16	−17·62	+51·54
O	..	−1·51	−3·02	−4·55	− 6·06	− 7·60	− 1·02	+ 5·60	+12·15	+10·60	+9·10	+7·60	+6·06	+4·55	+3·02	+1·51	..	+60·19	−23·76	+36·43
P	..	−1·30	−2·48	−3·75	− 5·02	− 6·27	− 7·52	+ 1·25	+10·02	+ 8·77	+7·52	+6·27	+5·02	+3·75	+2·48	+1·30	..	+46·38	−26·34	+20·04
Q	..	−0·71	−1·45	−2·20	− 2·95	− 3·70	− 4·45	− 5·10	+ 5·85	+ 5·10	+4·45	+3·70	+2·95	+2·20	+1·45	+0·71	..	+26·41	−20·56	+ 5·85

then measuring from the previous intersection to the one last obtained gives the strain on the bar 16, and measuring horizontally from the same intersection to the point Z gives the strain on the member H in the top boom. Then from this last intersection set up the line 15 parallel to the bar 15 in sketch, and from X draw the line K parallel to the member K in sketch until it intersects 15; measuring from the last intersection to this one will give the strain on 15, and measuring from the same to X will give the strain on the member K, and so on until the whole polygon of forces is completed for that load, which strains are tabulated in Table V.

In some of these diagrams it has been impossible to put the whole of the letters and figuring on, some of the figures being so small that it would only have led to confusion; however, in all the diagrams the strains owing to the reaction R_2 are multiples of each other, therefore they will all be readily understood from Fig. 7; and with regard to the other portions of the diagrams enough letters and figures have been put to render them intelligible.

The results are tabulated in Table V., and they can be verified as to the forces acting about any point, keeping that point in the polygon in equilibrium in the same manner as was shown for the arch at page 19.

It may appear strange, at first sight, on examining the Tables, to find that for a single load at the centre W_8 that both the bars C and C_1 are superfluous bars, but it merely shows, when the strains are tested, that the arch girder would theoretically support this load if hinged at the points of junction of O and P, and O_1 and P_1. Similarly that for all weights to the left of the centre, the arch could be hinged at the point of junction of O_1 and P_1.

In actual practice, however, it will be evident that the maximum strains would have to be used for a live load of 1 ton per foot run on an arch bridge of this description, which would give on

Top Boom.

H	G	F	E	D	C	B	A
+8·34	+18·05	+29·02	+41·30	+53·09	+60·38	+74·21	+80·00

ARCH.

J	K	L	M	N	O	P	Q
+85·94	+81·46	+77·70	+74·14	+69·16	+60·19	+46·38	+26·41

BARS.

17	16	15	14	13	12	11	10
+16·12	−15·69	+17·55	−15·86	+16·50	−16·07	+14·86	−15·94

9	8	7	6	5	4	3	2	1
+14·40	−18·08	+14·36	−22·37	+14·28	−26·86	+13·50	−28·35	+5·00

The above strains would therefore have to be added to those of the bridge equally loaded with its own weight, whereby stability would be ensured.

The above method and figures would be the one to use for a bridge where the diagonals are replaced by a web-plate, as this gives the greatest strain on the verticals; this would enable one to calculate the thickness of the webs in the same manner as for an ordinary plate girder. If an example had been given of this arch (which is unnecessary, as it is given in the next Example for a similar arch), with the diagonals in the reverse direction, it would have given tensile strains on the verticals, therefore the verticals in this example have the greatest strain which can possibly come upon them.

Example II.

Next take the foregoing arch girder, 80 feet span, 8 rise or versed sine, and 2 feet deep at crown, without verticals, but latticed as shown, Fig. 1, Plate VII., by the lines in black, loaded as before with 5 tons on each apex, the horizontal thrust for this would be

	T_1 or T_2	R_1	R_2
W_1	1·25	4·6875	0·3125
W_3	3·75	4·0625	0·9375
W_5	6·25	3·4375	1·5625
W_7	8·75	2·8125	2·1875
W_9	8·75	2·1875	2·8125
W_{11}	6·25	1·5625	3·4375
W_{13}	3·75	0·9375	4·0625
W_{15}	1·25	0·3125	4·6875
	T = 40·000		

Laying this thrust down horizontally, Fig. 2, Plate VII., and setting up the weights vertically, we obtain the strains

TABLE VI.

TABLE of the STRAINS on the ARCHED BRIDGE, Fig. 1, Plate VII., as SHOWN by the LINES in BLACK.

Compression +. *Tension* −.

BARS.

	W_1	W_3	W_5	W_7	W_9	W_{11}	W_{13}	W_{15}	Greatest Compression. +	Greatest Tension. −	Fully Loaded.
8	+5·75	+3·72	+ 1·65	−0·40	− 1·25	−0·95	−0·55	−0·18	+11·12	− 3·33	+ 7·79
7	−0·20	−4·20	− 1·85	+0·50	+ 1·45	−1·05	+0·65	+0·20	+ 3·85	− 6·25	− 2·40
6	+0·07	+6·55	+ 3·70	+0·80	− 0·55	−0·37	−0·22	−0·07	+11·12	− 1·21	+ 9·91
5	−0·09	−0·30	− 4·70	−1·05	+ 0·70	+0·45	+0·30	+0·09	+ 1·54	− 6·14	− 4·60
4	−0·15	−0·50	+ 7·15	+3·30	+ 1·10	+0·80	+0·50	+0·15	+13·00	− 0·65	+12·35
3	+0·21	+0·70	+ 1·15	−4·55	− 1·60	−1·15	−0·70	−0·21	+ 2·06	− 8·21	− 6·15
2	−0·62	−1·82	− 3·10	+6·85	+ 4·35	+3·10	+1·82	+0·62	+16·74	− 5·54	+11·20
1	+0·75	+2·20	+ 3·75	+5·20	− 5·20	−3·75	−2·20	−0·75	+11·90	−11·90	nil
					TOP BOOM.						
D	+2·67	+4·25	+ 1·85	−0·50	− 1·42	−1·07	−0·62	−0·21	+ 8·77	− 3·82	+ 4·95
C	+2·81	+8·75	+ 7·85	+0·80	− 2·30	−1·65	−1·02	−0·32	+20·21	− 5·29	+14·92
B	+2·50	+7·47	+12·50	+7·47	nil	nil	nil	nil	..	..	+29·94
A	+1·25	+3·75	+ 6·25	+8·75	+ 8·75	+6·25	+3·75	+1·25	..	..	+40·00
					ARCH.						
E	−1·42	+2·20	+ 5·87	+9·52	+ 9·87	+7·10	+4·25	+1·42	+40·23	− 1·42	+38·81
F	−1·55	−4·65	+ 2·20	+9·02	+10·82	+7·77	+4·65	+1·55	+36·01	− 6·20	+29·81
G	−1·46	−4·40	− 7·35	+5·42	+10·35	+7·35	+4·40	+1·46	+28·98	−13·21	+15·77
H	−0·70	−2·05	− 3·45	−4·85	+ 4·85	+3·45	+2·05	+0·70	+11·05	−11·05	nil

for the arch equally loaded with half a ton per foot run, which results are tabulated in the last column of Table VI., but the body of the Table, as in all previous cases, was obtained for each load separately, and an example of the diagram is given for constructing the polygon of forces for the single load by Fig. 4, Plate VII.

Example III.

Again, take this arch girder as shown by the dotted lines, Fig. 1, Plate VII., loaded as before with 5 tons on each apex; the horizontal thrusts and reactions for which would be—

	T_1 or T_2	R_1	R_2
W_2	2·50	4·375	0·625
W_4	5·00	3·75	1·250
W_6	7·50	3·125	1·875
W_8	10·00	2·50	2·50
W_{10}	7·50	1·875	3·125
W_{12}	5·00	1·250	3·75
W_{14}	2·50	0·625	4·375
	T = 40·00		

With this triangulation $\frac{1}{2}$ W or $\frac{W}{2}$ goes directly on to the abutments by the bars 9 and 9'. Laying this thrust T down as shown in Fig. 3, Plate VII., and setting up the weights vertically, the strains on the various bars are obtained for the arch girder loaded with half a ton per foot run, as tabulated in the last column of Table VII.; the body of the Table having been compiled, as before, by taking each load separately, and the method of drawing this diagram is shown by Fig. 5, Plate VII.

Now by adding the results of the last columns of Tables VI. and VII., it will give the strain for a double diagonally braced arched bridge fully loaded with 1 ton per foot run, with the following results:—

Top Boom.

M	D and M	D and L	C and L	C and K	B and K	B and J	A and J
..	4·95	4·95	14·92	14·92	29·94	29·94	40·00
..	1·27	7·87	7·87	19·89	19·89	34·13	34·13
1·27	6·22	12·82	22·79	34·81	49·83	64·07	74·13

TABLE VII.

TABLE of the STRAINS on the ARCHED BRIDGE, Fig. 1, Plate VII., as SHOWN by the DOTTED LINES.

Compression +. *Tension* −.

BARS.

	$\frac{W}{2}$	W_2	W_4	W_6	W_8	W_{10}	W_{12}	W_{14}	$\frac{W}{2}$	Greatest Compression. +	Greatest Tension. −	Fully Loaded.
9	+2·50	+3·40	+ 1·80	+ 0·22	− 1·37	−1·05	−0·70	−0·35	− nil	+ 7·92	− 3·47	+ 4·45
8	..	−4·00	− 2·15	− 0·30	+ 1·60	+1·20	+0·80	+0·40	..	+ 4·00	− 6·45	− 2·45
7	..	+6·14	+ 3·77	+ 1·35	− 1·10	−0·80	−0·60	−0·30	..	+11·26	− 2·80	+ 8·46
6	..	−0·32	− 4·45	− 1·60	+ 1·35	+0·95	+0·65	+0·32	..	+ 3·27	− 6·37	− 3·10
5	..	−0·05	+ 6·92	+ 3·60	+ 0·17	+0·10	+0·10	+0·05	..	+10·94	− 0·05	+10·89
4	..	+0·07	+ 0·12	− 4·77	− 0·22	−0·17	−0·12	−0·07	..	+ 0·19	− 5·35	− 5·16
3	..	−0·73	− 1·45	+ 7·20	+ 3·00	+2·20	+1·45	+0·73	..	+14·58	− 2·18	+12·40
2	..	+1·00	+ 2·00	+ 3·00	− 3·95	−3·00	−2·00	−1·00	..	+ 6·00	− 9·95	+ 3·95
1	..	−1·60	− 3·17	− 4·82	+ 6·40	+4·82	+3·17	+1·60	..	+15·99	− 9·59	+ 6·40
TOP BOOM.												
M	..	+2·12	+ 1·12	+ 0·15	− 0·83	−0·65	−0·42	−0·22	..	+ 3·39	− 2·12	+ 1·27
L	..	+5·58	+ 6·25	+ 1·97	− 2·42	−1·75	−1·17	−0·59	..	+13·80	− 5·93	+ 7·87
K	..	+5·48	+11·00	+ 8·55	− 2·06	−1·56	−1·05	−0·47	..	+25·03	− 5·14	+19·89
J	..	+3·96	+ 7·92	+11·92	+ 4·15	+3·07	+2·07	+1·04	..	..	..	+34·13
ARCH.												
N	..	+2·67	+ 5·35	+ 8·02	+10·72	+8·02	+5·35	+2·67	..	..	..	+42·80
O	..	−2·98	+ 1·95	+ 6·92	+11·95	+8·95	+5·97	+2·98	..	+38·72	− 2·98	+35·74
P	..	−3·11	− 6·22	+ 3·05	+12·50	+9·35	+6·22	+3·11	..	+34·23	− 9·33	+24·90
Q	..	−2·40	− 4·80	− 7·20	+ 9·57	+7·20	+4·80	+2·40	..	+23·97	−14·40	+ 9·57

ARCH.

E and N	E and O	F and O	F and P	G and P	G and Q	H and Q
38·81	38·81	29·81	29·81	15·77	15·77	nil
42·80	35·74	35·74	24·90	24·90	9·57	9·57
81·61	74·55	65·55	54·71	40·67	25·34	9·57

BARS.

	9	8	7	6	5	4	3	2	1
Black lines	..	+7·79	−2·40	+9·91	−4·60	+12·35	−6·15	+11·20	nil
Dotted	+4·45	−2·45	+8·46	−3·10	+10·89	−5·16	+12·40	−3·95	+6·40

By the above it will be seen that this would be a lighter arch than in Example I., which is owing to the weights being more directly transmitted on to the abutments.

In the arch bridge, when fully and equally loaded, and braced as shown by the lines in black, it will be observed that the bars H, H_1, 1, and 1′, have no strain on them, or, in other words, that the two halves of the structure would stand with the top distance piece of the boom from W_7 to W_9 between them. Likewise, as is shown by the triangulation in dotted lines similarly with the arch proper, all strains pass through the crown at the point W_8, as if the bridge were hinged at that point. However, in actual construction the maximum strain would have to be used for the live load. It has not been considered necessary to give an example as to the construction of the diagram for the bridge when half loaded, as it does not give the maximum strains to which the structure may be subjected with any other distribution of the load, and is therefore valueless; the diagrams for the girder fully loaded, giving the strains for the weight of the superstructure, having to be added to the maximum strains derived from the rolling load, and the values for the latter must be obtained by separate diagrams and tabulated.

It will be apparent that the calculations and diagrams for the arched bridge would equally apply for the rigid suspension bridge—that is, a bridge similar in construction to the Lambeth Bridge over the Thames, but built with Ravenhill's links and pin-joints instead of wire rope for the suspending chain.

The only difference in the calculation would be that all compressions would be tensions, and tensions be compressions, which is manifest by simply turning Fig. 1, Plate V., upside down. Very light and rigid structures might be constructed by using steel in this manner, which could with safety be worked to a higher factor than for wrought iron. It will also be patent, from the foregoing results, that in a bridge built like the Vauxhall Bridge over the Thames, where there is no triangulation between the arch-ring and top boom, that all that portion above the arch-ring, being only vertical bars and platforms, does not give any stability to the bridge, but is only so much dead weight.

Although the examples given for the arch girder have the top boom horizontal, still it would have been just as easy to have shown the diagrams for an arched girder with a camber or rise given in the top boom, as this would have only made the diagrams assimilate more closely to those for the arch. Also supposing there were a centre span with a camber having two side-spans, carrying the "sweep" to the abutments, there would not be the slightest difficulty in arriving at the strains on the side-spans, which would be deeper one end than the other, by the previous methods.

There is no doubt that once engineers get confidence in, and have a lucid and reliable proof of the strains affecting arched structures, that they will in time, for large spans, and where good foundations are to be obtained, much prefer them to either the girder with parallel booms, or the bow-string, as there is a considerable amount of weight, and therefore cost, to be saved in the first instance, and they are so much easier of erection in the next. This would be a still greater advantage for India or the Colonies, or wherever good foundations and good bricks or stone and mortar are to be procured, because, owing to the saving in weight, there would be less freight and inland carriage from the port of landing.

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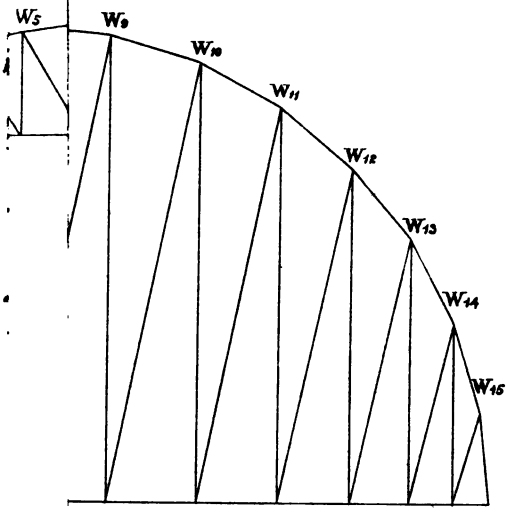
Plate 1.



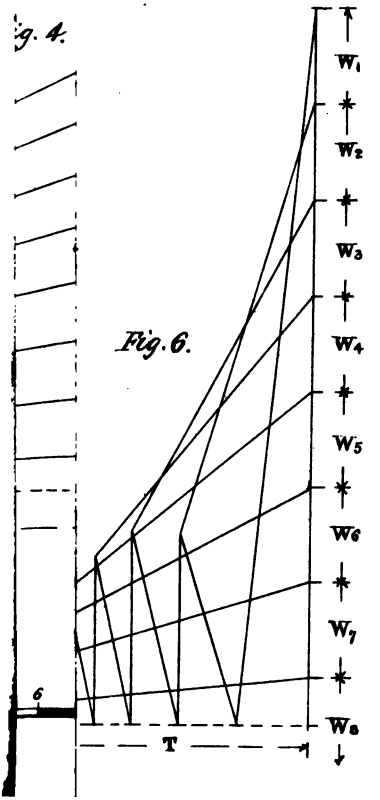


Fig. 4.

Fig. 6.

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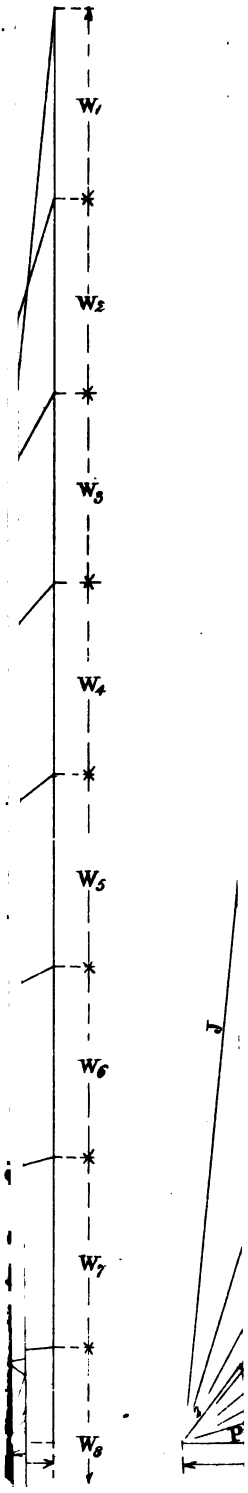
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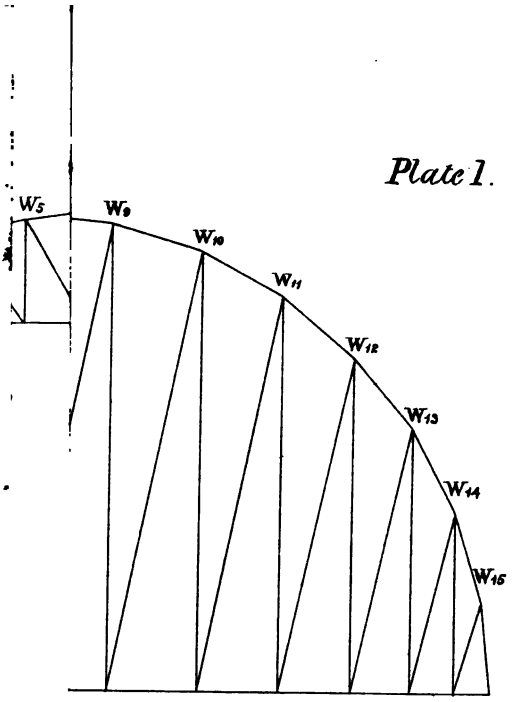
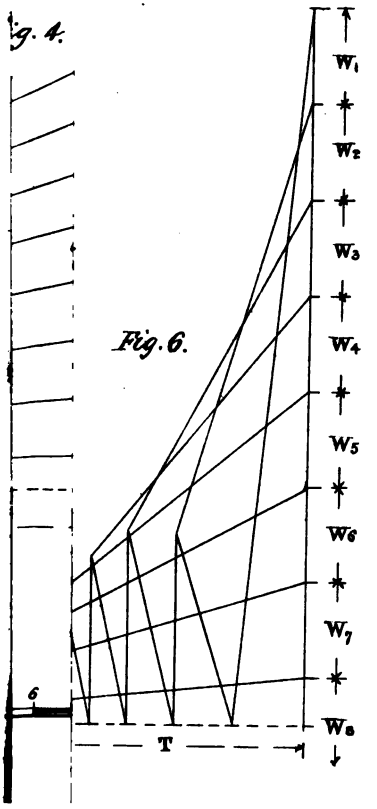
Plate 1.



g. 4.

Fig. 6.



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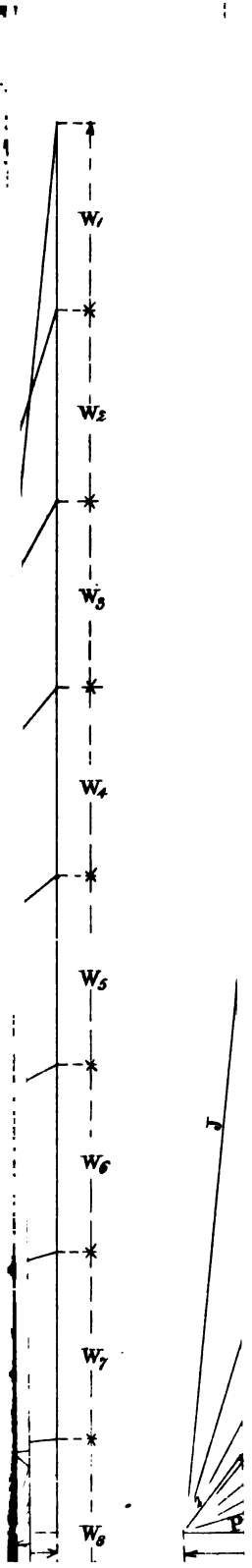
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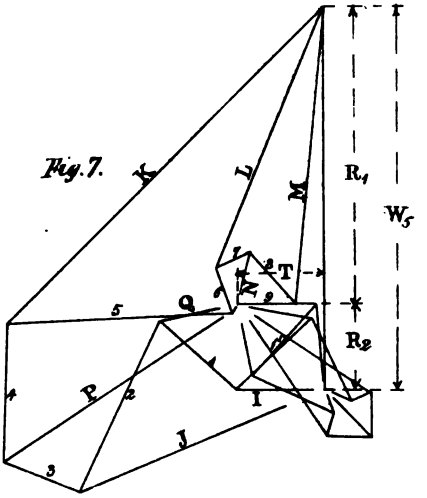
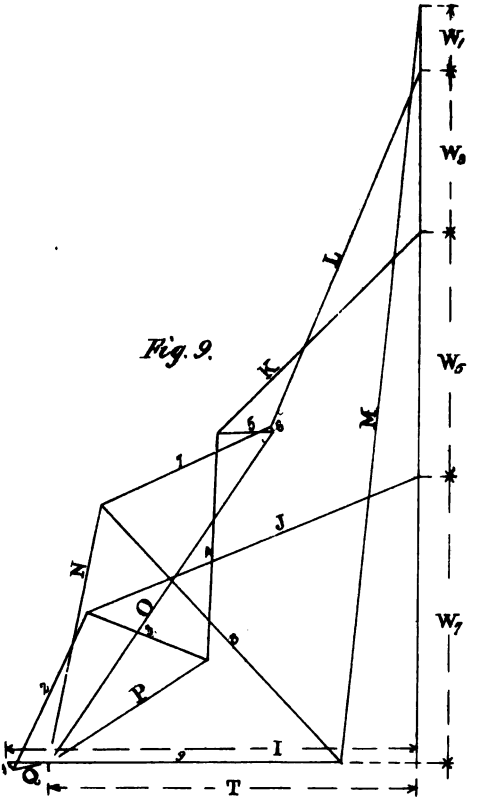
Plate IV.





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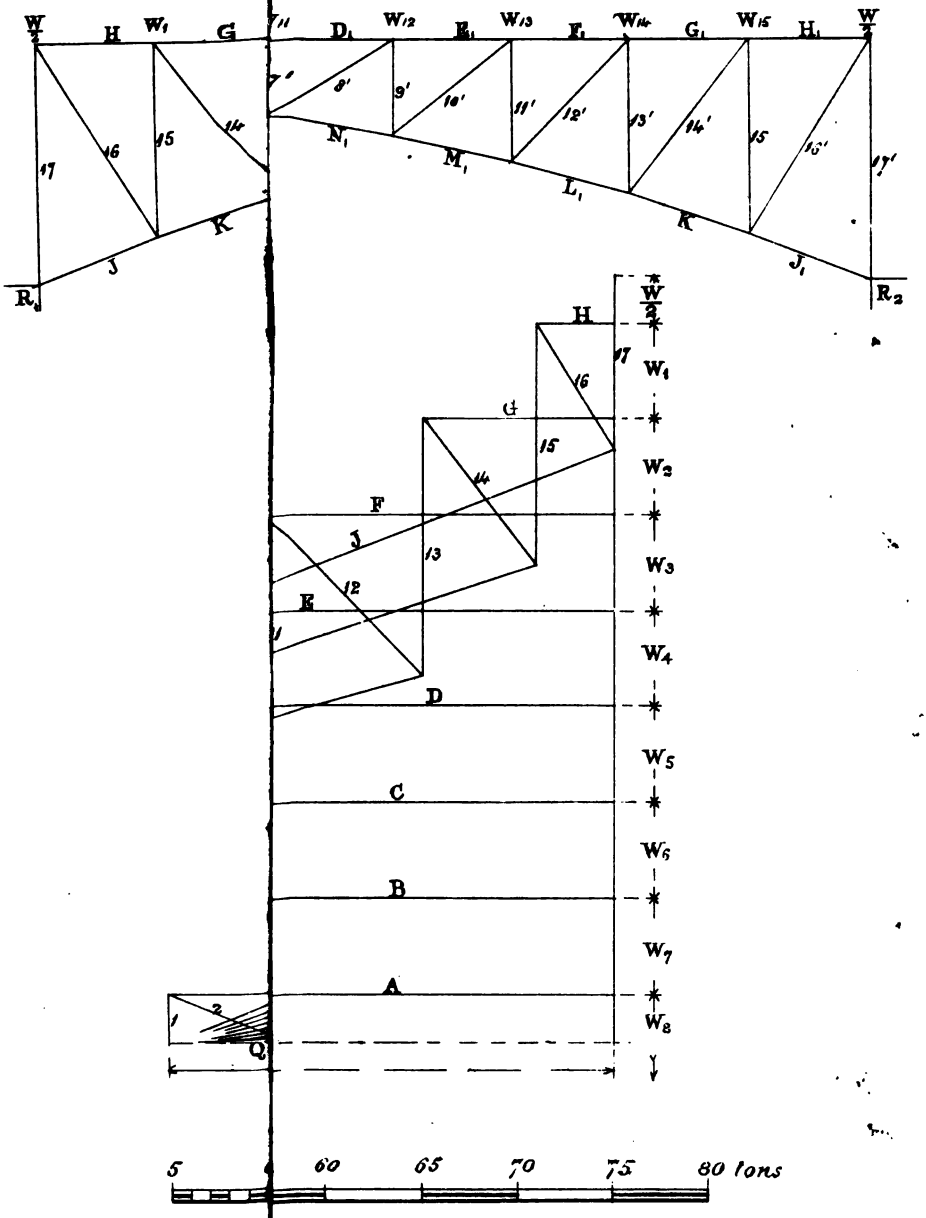

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Fig. 4.
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Fig. 8.
A
J
K

Fig. 4.

Plate VI.

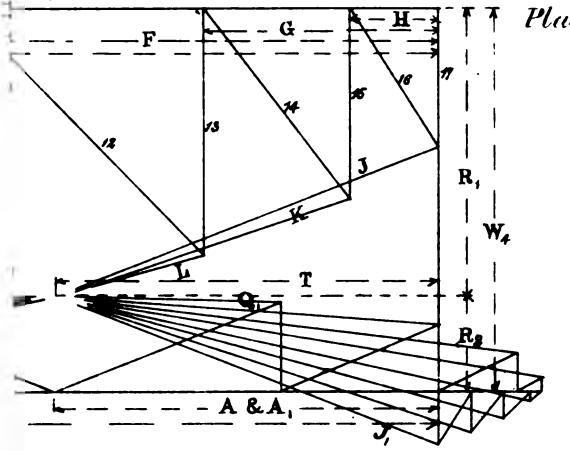

Fig. 6.

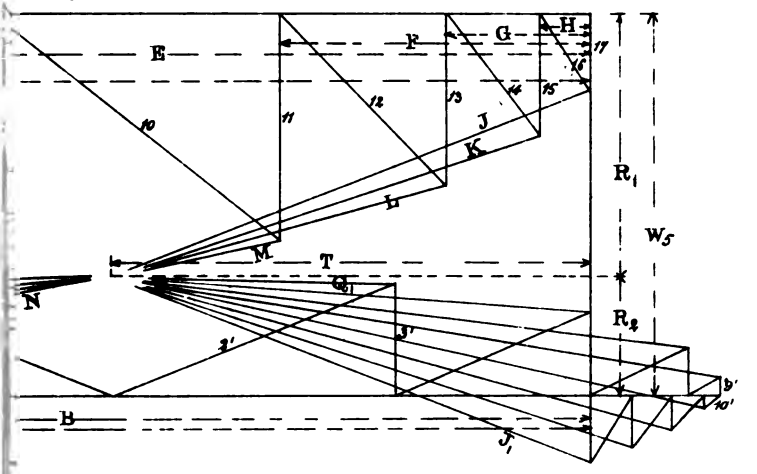

Fig. 8.

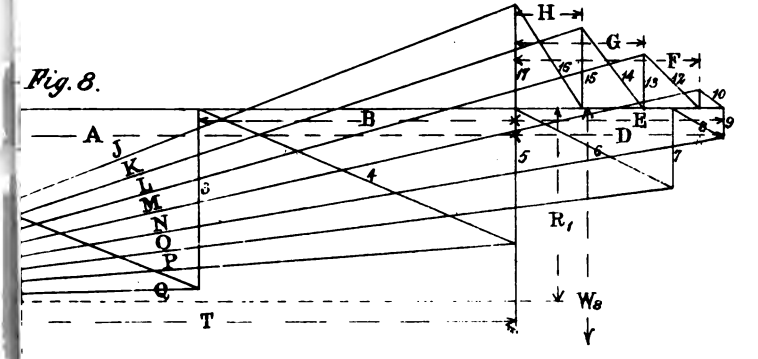

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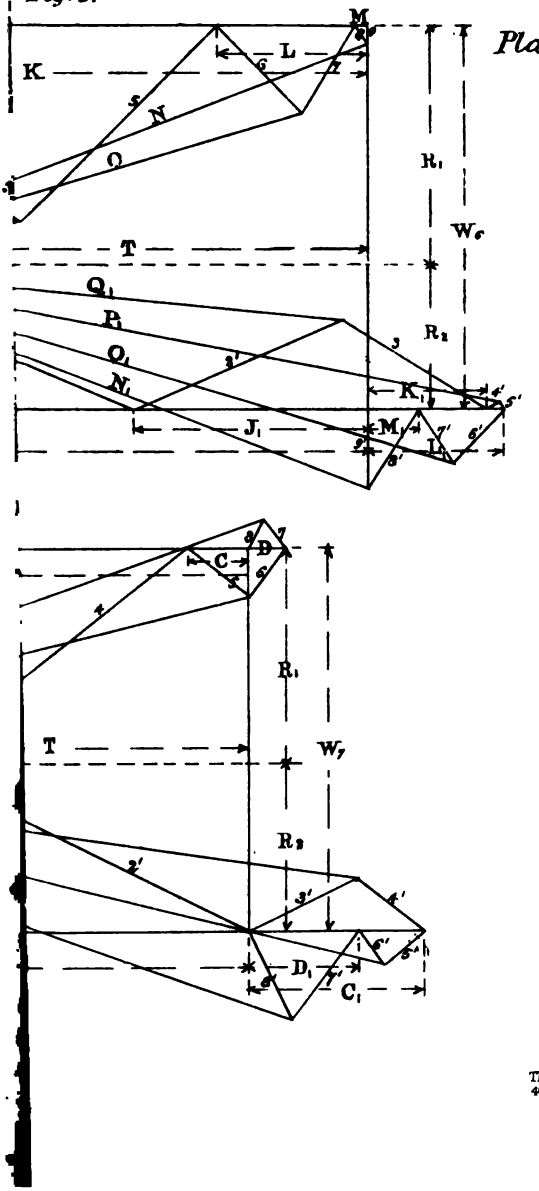
Fig. 5.

Fig. 5.

Plate VII.



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